2016

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Experimental Investigation on the Influence of Refrigerant Charge on the Performance of Trans-critical CO_2 Water-Water Heat Pump

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ABSTRACT

For the environmentally aware, natural refrigerant such as CO_2 is recommended and pursued by researchers for refrigerators. In this paper, a transcritical CO_2 heat pump system was set up to investigate the influence of refrigerant charge on the performance of a small-sized heat pump water heater. The transcritical CO_2 heat pump system was composed of a rotary compressor, a tube-in-tube evaporator and gas cooler, an electronic expansion valve (EEV), and an internal heat exchanger (IHX). Based on the experimental results, the effects of refrigerant charge on the key pressures, mass flow rate, power consumption, discharge temperature, superheat, heating capacity and coefficient of performance (COP) were analyzed with different EEV openings. The pressure in the evaporator and gascooler increased with the rise of refrigerant charge. The mass flow rate increased with the refrigerant charge range from 0.6kg to 2.2kg. The experimental results showed that the COP of the system was strongly related to CO_2 mass charge and had a maximum value at a specific CO_2 mass charge. Undercharged CO_2 systems could result in a fast decrease of the heating capacity and COP. The COP reduced more significantly at undercharged conditions than at overcharged conditions as the refrigerant charge further deviated from optimal charge. As EEV opening increased from 40% to 60%, the optimal COP decreased. And with the increase of EEV opening, the corresponding charge amount of optimal COP reduced.

1. INTRODUCTION

Since CFC and HCFC were restricted because of the environmental issues, researchers are working on the feasible and effective alternative refrigerants. Substantially, CO_2 is one of the representatives (Fatih *et al.*, 2014; Kim *et al.*, 2004). Some properties such as zero ODP, ignorable GWP, excellent heat transfer properties, high volume capacity and the cheap price achieve the unique nature of CO_2 in refrigerating systems. In 1993, a CO_2 transcritical refrigeration system in automotive air conditioning was built and tested (Antonijevic, 2008; Lorentzen and Pettersen, 1993). As time goes on, CO_2 transcritical refrigeration technology are wildly applied in vehicles, water heaters, heat pumps and low temperature cascade refrigerators, and so on.

The efficiency of the heat pump system is affected by many factors. The amount of refrigerant charge in the heat pump is a primary parameter that influences the energy efficiency. Undercharge or overcharge of refrigerant degrade its performance and deteriorates the system's reliability. Therefore, the heat pump should be charged with an optimal amount of refrigerant to achieve high performance. However, it is difficult to calculate the optimal charge accurately because of the various components and operating parameters. In recent years, researches on the lubricating oil, compressor, heat exchanger structure design, the flow and heat transfer performance and system design have made great progress. But investigations about influence of refrigerant charge amount on the performance of transcritical CO_2 heat pump are limited.

Eric and Steven (2000) analyzed the effect of refrigerant charge level on an automotive refrigeration system .They found that a reduction in the amount of refrigerant charge results in excessive compressor cycling, a lower condenser pressure, a higher refrigeration temperature, and an increase in the amount of superheat. J.M. and

Y.C.(2002) investigated the effects of off-design refrigerant charge on the performance of a water-water heat pump by varying refrigerant charge amount from -20% to +20% of full charge with the capillary tube and EEV. As a result, it was found out that the capillary tube system was relatively sensitive to refrigerant charge and outdoor load conditions. A similar work by Jongmin and Yongchan (2004) showed the effects of refrigerant charge on the performance of the water-to-water heat pump using R407C. Another water-to-water heat pump was investigated by Jose and Israel (2008). Their research presented the results and conclusions regarding the optimization of the charge obtained throughout a thorough development study performed with a reversible water-to-water heat pump using propane as refrigerant. Woohyun and James (2012) also proposed the similar research, but different refrigerant R22 was used in their experiment.
There are a few laboratory studies that documented the impact of refrigerant charge on the performance of a transcritical CO_2 heat pump. Honghyun *et al.*(2005) measured and analyzed the performance of the CO_2 heat pump by varying the refrigerant charge amount at standard cooling condition. However, the relationship between the optimized refrigerant charge and EEV opening was not investigated. Moreover, the pump they used was air source heat pump, and there is no intermediate heat exchanger in their experimental setup. In this paper, a transcritical CO_2 heat pump system was set up to investigate the influence of refrigerant charge on the performance of a small-sized heat pump water heater. The effects of refrigerant charge on the key pressures, mass flow rate, power consumption, discharge temperature, superheat, heating capacity and COP were analyzed with different EEV openings.

2. TEST FACILITY AND TEST PROCEDURE

2.1 Test Facility

As shown in Fig. 1, the present transcritical CO_2 heat pump system is composed of a rotary compressor, an evaporator, an electronic expansion valve (EEV), a gas cooler and an intermediate heat exchanger (IHX). The photograph of the test system is shown in Fig. 2. Table 1 lists the details about the main components in the system. Two of the cyclic water system which contains a thermostatic water tank, a heater and a water pump are used to keep the thermal balance in both the gas cooler and the evaporator. The water inlet temperature and inlet flow rate can be achieved by a water temperature control device and a water flow control valve.

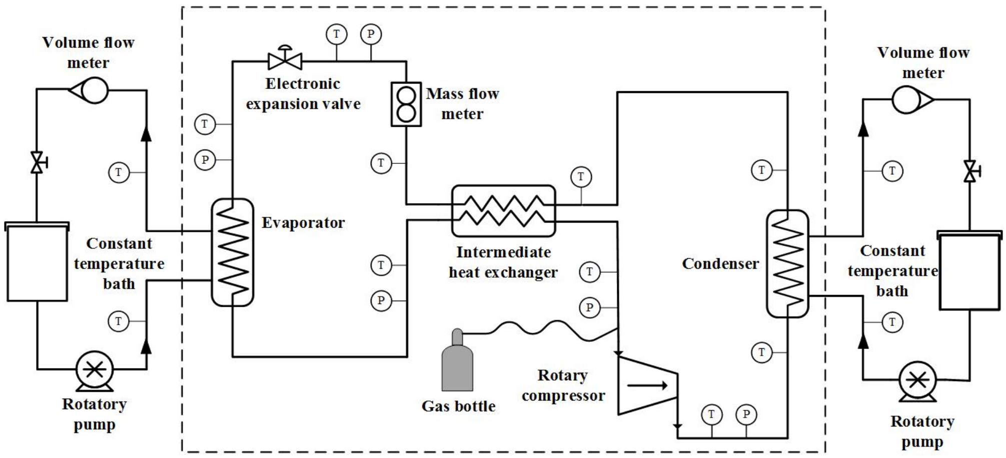

Figure 1: Schematic of the transcritical CO_2 heat pump system

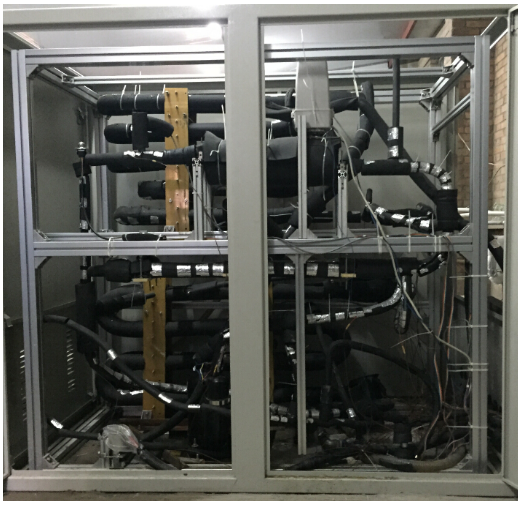

Figure 2: Photograph of the test system

The calibrated T-type thermocouples with the accuracy of ±0.5 ℃ (from -10.0 ℃ to 100.0 ℃) are used for measuring temperature. SAGINOMIYA HSK-BC150D pressure sensors with the accuracy of ±2.5 % in the pressure range from 0 MPa to 15.0 MPa gauge pressure are used for pressure measurement. The power consumption of the compressor is measured by a power meter with the accuracy of 0.1 % (pressure 10 V to 500 V, current 0.03 A to 40 A). The water flow rate in the evaporator is measured by a ±0.5 % accuracy turbine flowmeters (measurement range from 0.4 m^3/h to 8 m^3/h) and the water flow rate in the gascooler is measured by a ±0.5 % accuracy turbine flowmeters (measurement range from 0.1 m^3/h to 0.8 m^3/h). A SIMENS mass flow rate meter with an uncertainty of ±0.1 % (from 0 kg/h to 5600 kg/h) was used to measure the CO_2 mass flow rate. The YOKOGAWA MV2000 data recorder is used to obtain the data of temperature, pressure and the flow rate. The amount of the refrigerant charge is measured by a electronic scale with the accuracy of 50g (measurement range from 0 kg to 100 kg).

Table 1: Main Components.

Name of components	Main characteristic
Compressor	Rotary compressor; Stroke volume: 9.8 cm^3
Gas cooler	Tube-in-tube heat exchanger; Heat transfer area: 1.5 m^2
Evaporator	Tube-in-tube heat exchanger; Heat transfer area: 1.5 m^2
EEV	Electrically expansion valve and regulating valve. Port size: 2 mm
Intermediate heat exchanger	Tube-in-tube heat exchanger; The length of the tube: 2 m

2.2 Test Procedure

The first step of the test procedure is to determine the measurement system is working well. The second step is to adjust the water inlet temperature and water inlet flow rate in gascooler and evaporator. The water inlet temperature in the gas cooler and evaporator are 12℃ and 16.8℃ respectively and the water inlet flow rate in the gas cooler and evaporator are 0.2 m^3/h and 1.6 m^3/h respectively. In order to investigate the influence of refrigerant charge on the system, the water inlet temperature and inlet flow rate were constant in the whole test.

For this transcritical CO_2 water-water heat pump system, the refrigerant was added into the heat pump in a 200 g increment until the evaporating temperature has increased slowly. Specifically, the principle of the refrigerant charging is that the evaporating temperature should keep between -5℃ and 16℃. In this study, the EEV opening was varied from 40% to 60% in a 10% increment to investigate the influence of refrigerant charge on the power consumption, rejection pressure, discharge temperature, superheat, evaporating pressure, mass flow rate, heating capacity and coefficient of performance with different EEV openings.

3. RESULTS AND DISCUSSION

In this section, the experimental results on the effects of the refrigerant charge are presented and discussed. The system performance was evaluated with EEV opening added from 40% to 60% in a 10% increment. The water inlet temperature and inlet flow rate were constant in the whole test.

3.1 The effects of refrigerant charge on the key pressures

The effects of refrigerant charge on the pressures in evaporator and gascooler with different EEV openings were illustrated in Fig. 3 and Fig.4. As the refrigerant charge increased, the system pressure increased in both the gascooler and the evaporator. The pressure in evaporator increased rapidly at first, and then increased slowly. With the refrigerant charge ranging from 0.6kg to 2.2kg, the pressure in evaporator increased from 2.75MPa to 4.75MPa at 60% EEV opening. The pressure in gascooler increased linearly from 4MPa to 8.15MPa as the refrigerant charge ranged from 0.6kg to 2.2kg at 60% EEV opening.

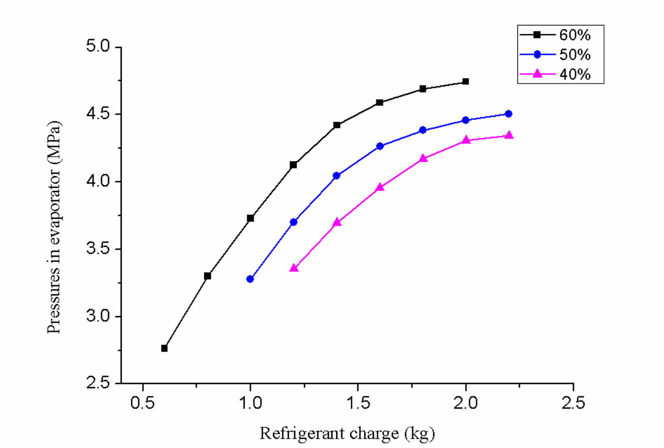

Figure 3: Variations of the pressures in evaporator with increase of refrigerant charge

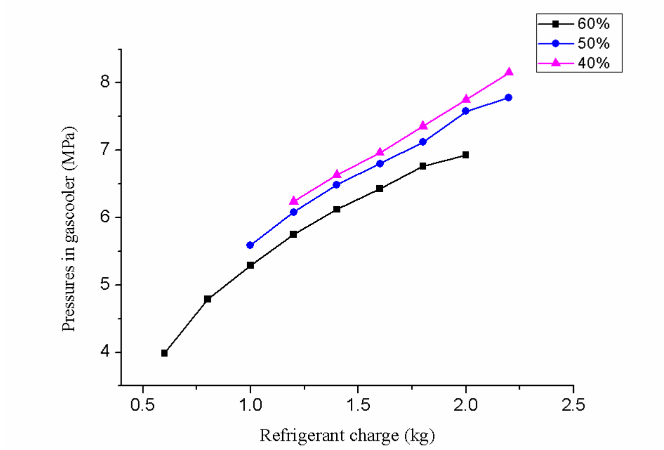

Figure 4: Variations of the pressures in gascooler with increase of refrigerant charge

Fig. 3 and Fig.4 also shows that different EEV openings lead to different pressures at the same charge level. As EEV opening increased from 40% to 60% at the same charge level, the pressure in gascooler decreased. However, it was the opposite situation in evaporator. This is because the small EEV opening led to greater resistance, but at the same time, the small EEV opening made a big pressure drop.

3.2 The effects of refrigerant charge on the mass flow rate

The variations of the system mass flow rate caused by the increase of refrigerant charge are shown in Fig. 5. The mass flow rate increased from 100kg/h to 280kg/h with the refrigerant charge ranging from 0.6kg to 2.2kg at 60% EEV opening.
Fig.5 also shows that different EEV openings lead to different mass flow rates at the same charge level. As EEV opening increased from 40% to 60% at the same charge level, the mass flow rate increased. This is because the large EEV opening led to a larger port size.

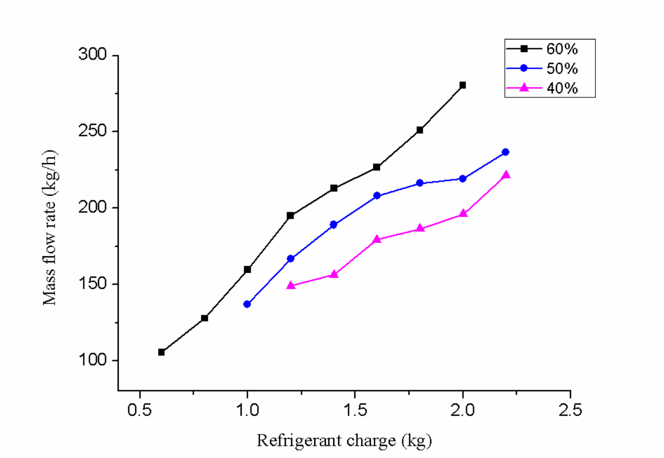

Figure 5: Variations of mass flow rate with increase of refrigerant charge

3.3 The effects of refrigerant charge on the power consumption

Fig. 6 shows the variation of compressor power consumption with the increase of refrigerant charge amount. The power consumption of the cycle increased steadily with the refrigerant charge ranging from 0.6kg to 2.2kg.It also can be seen from Fig.6 that different EEV openings led to different power consumptions at the same charge level. As EEV opening increased from 40% to 60% at the same charge level, the power consumption decreased. This is because the small EEV opening led to greater resistance.

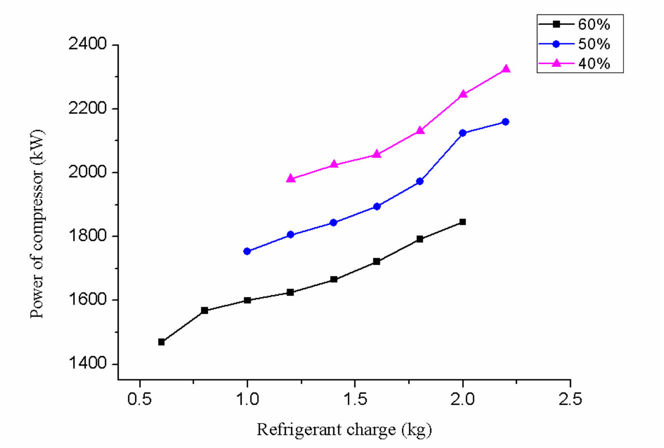

Figure 6: Variations of power consumption with increase of refrigerant charge

3.4 The effects of refrigerant charge on the discharge temperature and superheat

Fig.7 represents the superheat of the CO_2 heat pump systems. In the system, the superheat reduced as the refrigerant charge increased due to the rise of the refrigerant flow rate through the evaporator. The superheat was maintained at nearly zero at 2.2kg charge amount. This may cause wet compression and serious damage to compressors. It also can be seen from Fig.7 that different EEV openings led to different superheats at the same charge level. As the EEV opening increased from 40% to 60% at the same charge level, the superheat decreased due to increase of mass flow rate.

Fig.8 shows the discharge temperature of the system with a variation of refrigerant charge. The discharge temperature increased gently with a reduction of charge amount due to the rise of superheat and a decrease of mass flow rate. Fig.8 also illustrates that different EEV openings led to different discharge temperatures at the same charge level. As EEV opening increased from 40% to 60% at the same charge level, the discharge temperature decreased due to the decrease of superheat.

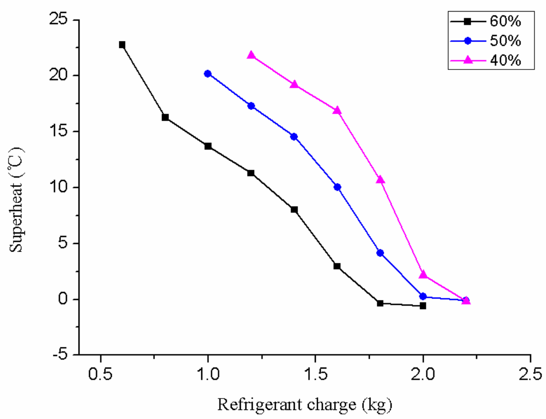

Figure 7: Variations of superheat with increase of refrigerant charge

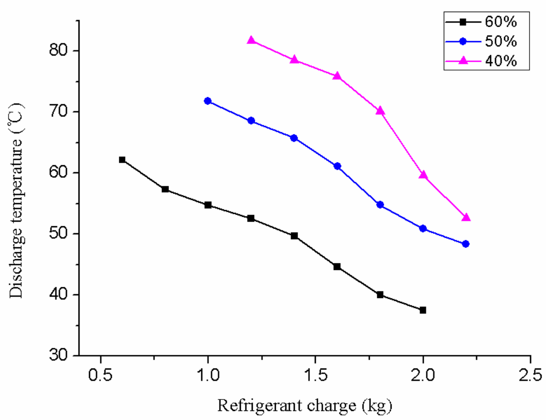

Figure 8: Variations of discharge temperature with increase of refrigerant charge

3.5 The effects of refrigerant charge on the heating capacity and system performance

Fig.9 shows the variation of heating capacity with the increase of refrigerant charge amount. With the increase of filling quantity, the heating capacity increased rapidly at first, reached its peak and then decreased slowly. The slope of the capacity with charge amount was much steeper under undercharged conditions than that at overcharged conditions. Fig.9 also shows that different EEV openings led to different heating capacities at the same charge level. As EEV opening increased from 40% to 60% at the same charge level, the heating capacity decreased due to decrease of discharge temperature.

Fig.10 shows the COP of the CO_2 heat pump system with increase of refrigerant charge amount. The COP had a maximum value at a specific CO_2 mass charge. With the increase of filling quantity, the COP increased rapidly at first, reached its peak and then decreased slowly. In the system, as the charge amount deviated from the full charge, the reduction of COP was a little more significant in undercharged conditions than that at overcharged conditions. In undercharged conditions, the COP was rapidly reduced with decrease of charge amount due to a rapid decrease of heating capacity. Fig.10 also shows that different EEV openings led to different COP at the same charge level. As EEV opening increased from 40% to 60%, the optimal COP decreased. And with the increase of EEV opening, the corresponding charge amount of optimal COP reduced.

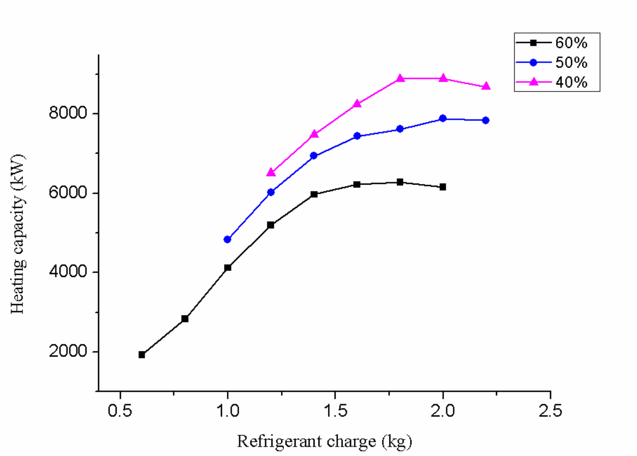

Figure 9: Variations of heating capacity with increase of refrigerant charge

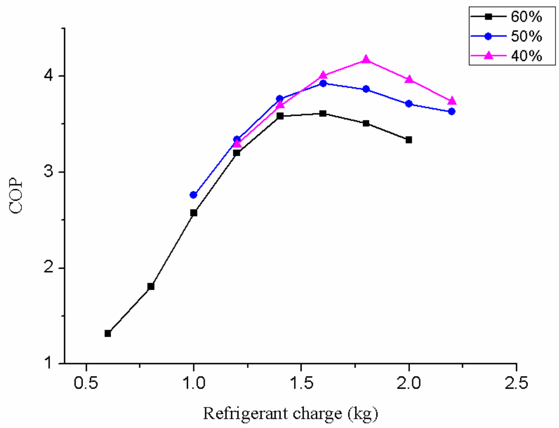

Figure 10: Variations of COP with increase of refrigerant charge

4. CONCLUSION

The effects of refrigerant charge amount on the performance of the transcritical CO_2 water-water heat pump system with different EEV openings were measured and analyzed. The pressure in the evaporator and gascooler increased with the rise of refrigerant charge. The power consumption of the cycle increased with the refrigerant charge ranging from 0.6kg to 2.2kg.

The superheat reduced as the refrigerant charge increased due to the rise of the refrigerant flow rate through the evaporator. The superheat was kept at nearly zero at 2.2kg charge amount. This may cause wet compression and it may cause serious damage to the compressor. The discharge temperature increased gently with a reduction of charge amount due to the rise of superheat and decrease of mass flow rate. The COP has a maximum value at a specific CO_2 mass charge. With the increase of filling quantity, both heating capacity and COP increased rapidly at first, reached the peak and then decreased slowly. In the CO_2 system, the COP reduced more significantly in undercharged conditions than in overcharged conditions as the refrigerant charge further deviated from optimal charge. Different EEV openings led to different COP at the same charge level. As EEV opening increased from 40% to 60%, the optimal COP decreased. And with the increase of EEV opening, the corresponding charge amount of optimal COP reduced.

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ACKNOWLEDGEMENT

This project was supported by the National Nature Science Foundation of China (50976082), the Specialized Research Fund for the Doctoral Program of Higher Education (20130201110038) and the Fundamental Research Funds for the Central Universities.